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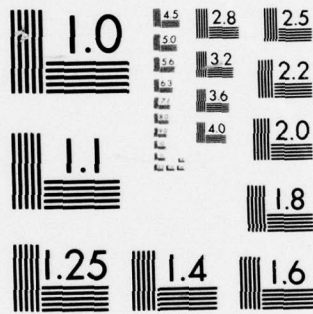
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A COMPACT, SEALED, SINGLE MODE TEA-CO₂ LASER

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M. Lacombe

DDC
JUL 25 1978
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RESUME

Nous avons construit et scellé un laser CO₂ compact fonctionnant selon la technique de la double décharge et l'avons fait fonctionner en mode fondamental. Plus de 10⁶ impulsions ont été obtenues en régime scellé grâce à l'addition de petites quantités d'hydrogène et de CO au mélange gazeux initial. Nous avons également démontré qu'il était possible de faire fonctionner ce laser sans hélium avec une puissance de sortie, en mode fondamental, de l'ordre de 35 mJ/impulsion et une puissance crête de 150 kW. Le taux de répétition était de 0.5 s⁻¹.

Dans le but d'obtenir l'oscillation dans le mode fondamental, nous avons gardé la longueur totale de la cavité du laser à 18 cm. Cette courte cavité permet l'oscillation d'un seul mode longitudinal quand la fréquence de la cavité est entretenue près de la fréquence centrale de CO₂. Des mesures de battement de fréquence, effectuées à l'aide d'un laser stabilisé CO₂ à onde entretenue, indiquent une déviation de fréquence d'environ 5-6 MHz/μs dans la queue de l'impulsion. (NC)

ABSTRACT

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A compact, sealed, TEA-CO₂ laser utilizing a double-discharge technique has been constructed and operated under single-mode conditions. Sealed operational lifetimes exceeding 10⁶ pulses have been obtained by the addition of small quantities of hydrogen and CO to the initial gas mixtures. It has also been found that operation without helium is possible giving single-mode output energies of about 35 mJ/pulse at peak powers of about 150 kW. The pulse repetition frequency was 0.5/s⁻¹.

To obtain single-longitudinal-mode operation, the laser cavity was kept at an overall length of 18 cm. This short laser cavity allowed the oscillation of only one longitudinal mode when the frequency of the cavity was tuned closely to the CO₂ line centre frequency. An iris was used to restrict transverse modes to the TEM₀₀. Beat frequency measurements using a stable, CW CO₂ laser indicate a "chirp" of about 5-6 MHz/μs in the tail of the pulse. (U)

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FIGURES 1 to 6

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1.0 INTRODUCTION

In many applications of interest, such as heterodyne laser radars, it could be advantageous to utilize a completely portable TEA-CO₂ laser. This would necessitate the development of a highly reliable sealed, single-mode laser.

The problem of obtaining the required operational lifetimes both at low-repetition rates (Stark et al Ref. 1, Shields et al Ref. 2) and at moderate-repetition rates (Pace and Lacombe Ref. 3) has been discussed previously. The same methods have been employed herein to obtain the necessary sealed operation. This entails the addition of small amounts of hydrogen and CO to the basic He-N₂-CO₂ gas mixture as was originally suggested by Stark et al (Ref. 1).

To be able to use the laser in a heterodyne application, it is essential that operation in a single-longitudinal mode be obtained. This has normally been achieved by using a hybrid configuration (the addition of a low-pressure gain section to the standard TEA gain section within the laser cavity). Lasers of this type have been reported by Gondhalekar et al (Ref. 4), Girard (Ref. 5), Gondhalekar et al (Ref. 6) and others. Single-mode operation has also been achieved by injection of a signal from a low-power-frequency-stable master oscillator into the high-power TEA laser cavity. These techniques have been reported by Buczek and Freiberg (Ref. 7), Buczek et al (Ref. 8), Clobes et al (Ref. 9), Lachambre et al (Ref. 10) and others. However, for use as a portable system both of these methods have their drawbacks, namely, the difficulty in physical size and power requirements. In the device presented herein, single-longitudinal-mode operation has been achieved by using a short cavity-length as has been suggested by Troitskii and Shebanin (Ref. 11). An 18-cm-long cavity gives an intermode frequency spacing of 0.833 GHz and thus, at atmospheric pressure, the gain-bandwidth of the small CO₂ laser is only sufficient to allow one longitudinal mode to oscillate, provided

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the length of the cavity is tuned to a value for which the frequency of the mode corresponds closely to the central frequency of the laser transition. Single-transverse-mode operation was obtained by the choice of mirror curvatures and by the insertion of an iris. Single-mode operation was verified by measurements with a fast photon drag detector and heterodyne-beat measurements with a stable CW-CO₂ laser determined the frequency "chirping" during the latter portion of the pulse.

To obtain the maximum single-mode energy from such a small discharge volume (10 x 10 x 100 mm³), we utilized a convex-concave resonator configuration as has been suggested by Chester and Maydan (Ref. 12). It was also found that we could operate the laser without helium at a reduced pressure of 54 kPa. Using this configuration we were able to obtain an output peak power of 150 kw in a 50 ns FWHM spike followed by a tail with a total duration of 1.8 μ s. The combination of reduced pressure and short cavity-length insured single-longitudinal-mode operation.

Results of the beat-frequency measurements indicate that there is a frequency 'chirp' of about 5-6 MHz/ μ s in the tail of the pulse. This work was performed at DREV between February and November 1977 under PCN 33H01, Applications des lasers en surveillance et télé-détection-générale.

2.0 LASER DESIGN

The laser module under study employs the double-discharge electrode structure described by Laflamme (Ref. 13). This laser design has been found to operate successfully in sealed as well as high-repetition-rate configurations (Pace and Lacombe Ref. 3). The basic structure has been described by Laflamme but a few minor modifications will be detailed.

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The laser structure consists of a trigger bar, a grid cathode and a solid aluminum anode. The trigger bar was wrapped in a dielectric sheet (12 turns 'Kapton') and situated about 2-3 mm behind the grid. In this type of laser the width and length of the discharge are controlled by the trigger bar and thus it is not necessary to shape the electrodes to a uniform-field profile as long as the flat surface of the electrodes is larger than the discharge. However, since it is necessary to provide a uniform pre-ionization in a plane normal to the main discharge electric field (Kline and Denes Ref. 14), a uniform-field electrode was constructed for the trigger bar (Chang Ref. 15). The grid was constructed from a 0.2 mm thick brass sheet perforated with 0.8 mm diameter holes giving a 55-60% transmission. The electrodes were arranged to be parallel and uniform to within 0.02 mm. The dimensions of the discharge volume were $10 \times 10 \times 100 \text{ mm}^3$.

The laser electrodes were mounted in a perspex tube with an inside diameter of 38 mm and a length of 180 mm. A schematic cross sectional diagram of the laser is shown in Figure 1(a).

The excitation system is depicted in Figure 1(b). It is basically a two-step process that involves the sequential discharging of the pre-ionization and the main discharge with the appropriate synchronization. The operation of this circuit has already been discussed by Lacombe et al (Ref. 16) and by Pace and Lacombe (Ref. 3).

To obtain the maximum single-mode energy from such a small discharge, it was decided to use a convex-concave resonator configuration as has been suggested by Chester and Maydon (Ref. 12). In this configuration a total reflector with a +500 cm radius-of-curvature was located 18 cm from a convex output mirror with a -500 cm radius-of-curvature and a reflectivity of 80%. Calculations indicate (Kogelnik and Li Ref. 17) that this resonator configuration is stable and should produce a fundamental mode volume that extracts a relatively large proportion of the energy from the small discharge volume. A complete

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analysis of this type of laser resonator has been performed by Chester and Maydan (Ref. 12). The results indicate that a $TEM_{0,0}$ mode can be produced with a measured beam divergence of 3.0 mrad full angle. This is about 1.8 times the diffraction limit for the 8 mm iris used in the cavity. Figure 2 shows a typical plot of beam energy density against radial distance in the optical far field. Both horizontal and vertical scans were essentially identical. It shows that the distribution is approximately Gaussian (solid line in Figure 2) as would be expected for single transverse mode operation. The corresponding total energy was about 35 mJ/pulse, which is about one half of that obtainable from a similar multimode laser. The peak power in single-mode operation was only slightly reduced from the multimode value. This is because of the sharper output spike as is normal in single-mode operation. In this case the single-mode peak output power was about 150 kw. Gas mixtures and typical operating conditions will be discussed in Section 4.0.

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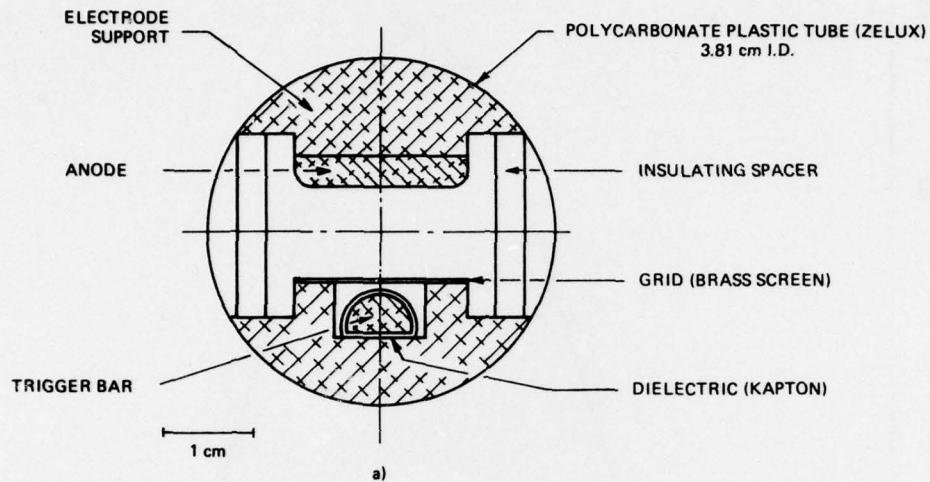


FIGURE 1(a) - Schematic cross sectional diagram of the laser

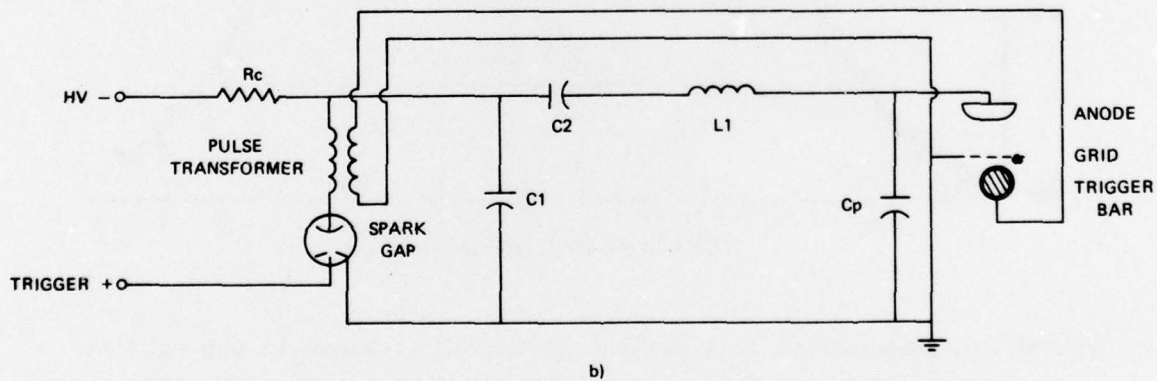


FIGURE 1(b) - Laser electrical excitation circuit

$C1 = 5.4 \text{ nf}$, $C2 = 5.4 \text{ nf}$, $L1 = 10 \text{ } \mu\text{H}$

$C_p = 2.7 \text{ nf}$, $R_c = 10 \text{ Meg. ohms}$

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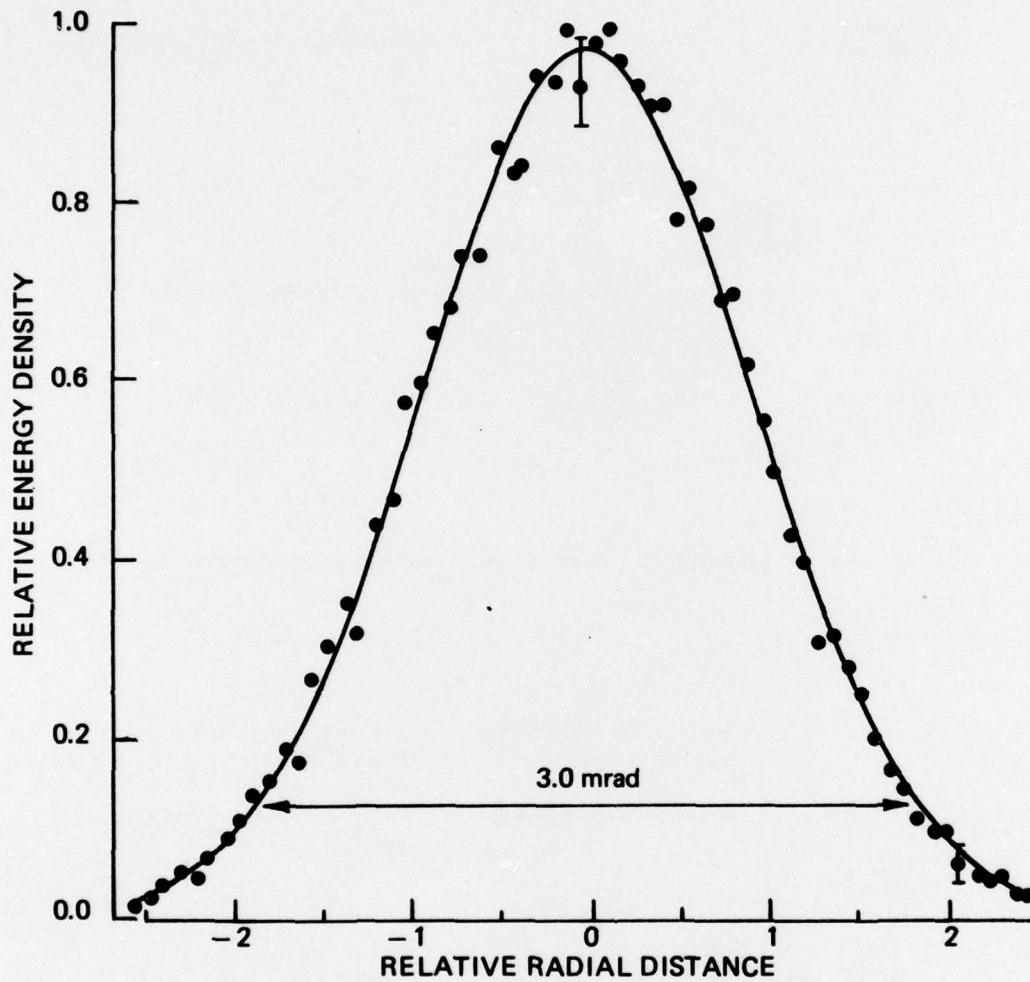


FIGURE 2 - Beam energy density against radial distance in the optical far field

3.0 SINGLE-MODE OPERATION

In order to be able to use the laser in a heterodyne radar application it is essential that single-longitudinal-mode operation be obtained. As mentioned above, this was accomplished by the use of a cavity only 18 cm long. This will give an intermode frequency separation of 0.833 GHz. At a pressure of 100 kPa the FWHM of the gain curve will be approximately 3.5 GHz for the rotational transitions (Alcock et al Ref. 18) in the P branch at 10.6 μm and should follow a relationship having the form:

$$\Delta\nu_L = \beta_{\text{CO}_2} P_{\text{CO}_2} + \beta_{\text{N}_2} P_{\text{N}_2} + \beta_{\text{H}_2} P_{\text{He}} = \beta_{\text{eff}} P_{\text{tot}} \quad [1]$$

The line-broadening coefficient (β_{eff}) has a value of 0.035 GHz/kPa (FWHM) where P is the pressure (Alcock et al Ref. 18). Using this expression and a Lorentzian gain curve we find that the number of longitudinal modes is approximately given by (Rigrod Ref. 19):

$$N \approx (4\ell/c) \Delta\nu_{\text{max}} \quad [2]$$

where $2\Delta\nu_{\text{max}}$ is the gain bandwidth above threshold, ℓ is the mirror separation and c is the speed of light. The gain for this type of laser discharge has been measured using the technique of Denes and Weaver (Ref. 20) and found to be about 2% per cm. This combined with an output coupling mirror of 80% reflectivity and the results presented in equation [2] should lead to at least three longitudinal modes. However, there are also the diffraction losses introduced by the 8-mm iris inserted into the cavity, but it is difficult to estimate these diffraction losses due to the uncertainty of about $\pm 5\%$ in the radius-of-curvature of the mirrors. This error in mirror curvature can lead to large errors in the estimated diffraction losses (Li Ref. 21). However, if one

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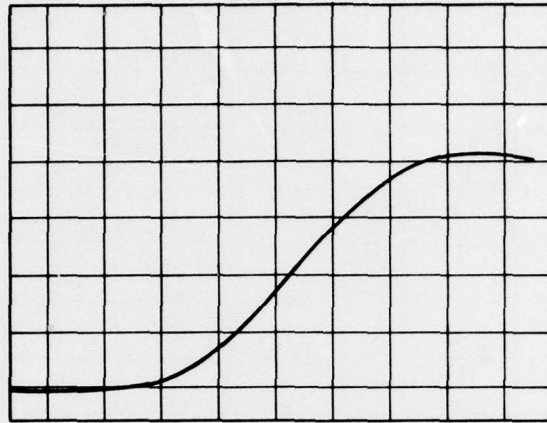
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assumes a Lorentzian lineshape it becomes necessary to have a minimum diffraction loss of about 2% per pass to insure single-longitudinal-mode operation. A diffraction loss of this magnitude would be compatible with the error limits on the radius-of-curvature of the mirrors.

To verify the above assumptions the output of the laser was analysed with a photon drag detector and recorded on a fast transient digitizer (risetime ≈ 1 ns). It should be noted that oscillation was observed on the P(20) transitions of the $10.6\mu\text{m}$ band. The laser cavity could be tuned using a piezo electric element to displace the total reflector. If the length of the cavity is tuned to a value for which the cavity frequency is close to the central laser transition frequency, only one longitudinal mode oscillates. Figure 3(a) indicates the results for operation under these conditions. The smooth curve obtained during the pulse risetime indicates no mode beating and thus single-mode operation. However, if the cavity length is detuned by $\lambda/4$, simultaneous oscillation on two cavity modes is seen. Figure 3(b) illustrates the results for operation in this regime. As can be seen a beat frequency of 0.833 GHz is observed which is the result of the beating of two successive modes located on either side of line centre. This type of operation has also been reported by Ernst (Ref. 22).

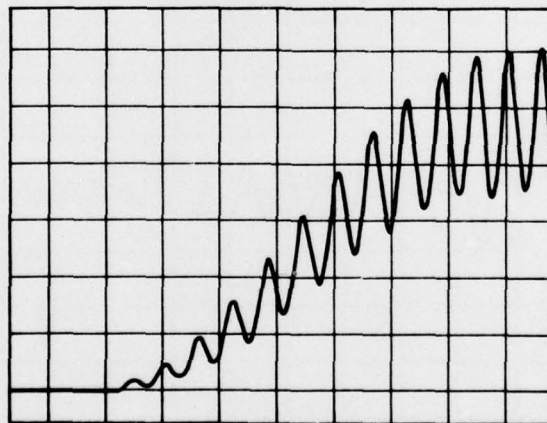
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a)

FIGURE 3(a) - Risetime of laser output pulse detected by the photon drag detector. The frequency of the mode has been tuned near line centre. The time scale is 2ns/div.

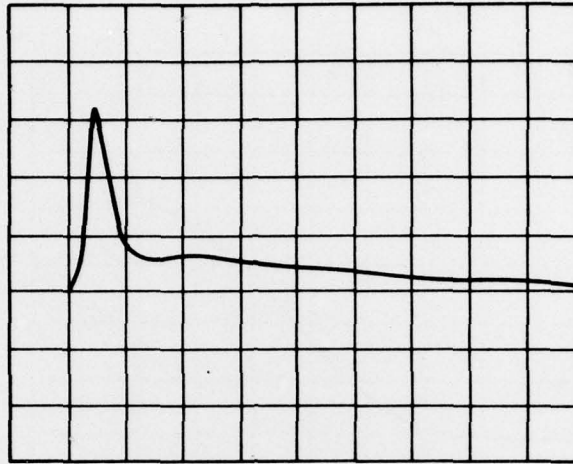


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FIGURE 3(b) - Risetime of the output pulse when the mode frequency has been detuned from line centre. The time scale is 2ns/div. The modulation frequency is 833 MHz.

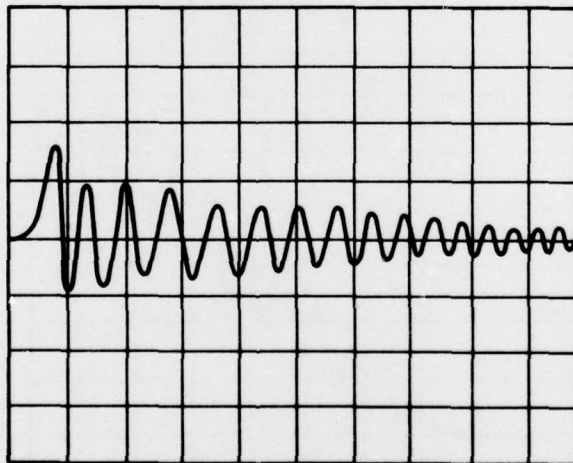
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FIGURE 4(a) - Laser pulse shape as measured with the Hg-Cd-Te detector.
The time scale is 100ns/div.



b)

FIGURE 4(b) - Heterodyne beat signal of the TEA laser with a stabilized
CW-laser. The time scale is 100ns/div. Note the frequency
sweeping apparent in the tail of the pulse.

3.1 Measurement of Frequency Sweeping ('Chirp')

As has been discussed previously (Weiss and Schnur Ref. 23) there appears to be a change in frequency of several megahertz in portions of the output pulse of a transversely excited CO_2 laser. In order to measure the magnitude of this effect in our laser, a heterodyne-detection technique (similar to Weiss and Schnur), utilizing a stabilized ($\pm 2\text{MHz}$) single-frequency CW CO_2 laser, has been employed. Figure 4(a) shows a typical pulse shape, and Figure 4(b) indicates a distinct beating signal superimposed on the pulse envelope of the TEA laser output. The frequency of this beat could be controlled by tuning the cavity of the TEA laser. The beat signal was measured with a Hg-Cd-Te photovoltaic detector operating at 77K and observed directly on the transient digitizer. The system bandwidth was estimated to be about 80 MHz. It should be noted that no attempt was made to stabilize the TEA laser and thus periodic adjustment of the cavity by means of the piezo electric translator was necessary to compensate for thermally induced changes. However, pulse-to-pulse initial frequency differences of only 2-3 MHz were recorded with a frequency drift of about $\pm 20\text{ MHz}$ over a 20 minute period.

The approximate instantaneous frequency has been determined from the period of each oscillation and plotted as a function of elapsed time from the beginning of the pulse. Figure 5 shows two examples for which the starting frequency is on opposite sides of the CO_2 line centre.

It can be seen that the frequency sweeping is similar both on the positive and negative sides of line centre. There is a slight decrease in absolute frequency and then a smooth increase. Previous investigations concerning the frequency sweep (Stiehl and Hoff Ref. 24, Lipchak Ref. 25) have attributed the 'chirp' to a change in the resonant

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electric susceptibility of the laser gain medium as its population inversion depletes rapidly during pulse formation. The refractive index of the gas is proportional to the real part of the resonant susceptibility, which is proportional to the real part of the inversion and the frequency separation of oscillation from line centre. In the case where the TEA laser operates farther from line centre than the local oscillator, the beat frequency in the rising part of the pulse should increase due to the relaxation in the real part of the resonant susceptibility as the inversion is depleted.

The type of behaviour observed indicates that this resonant phenomenon has little influence on the frequency characteristics of the system. Resonant effects would cause the 'chirp' to change sign depending on the position of the initial cavity-resonance with respect to CO₂ line centre. These resonant effects are not observed because of the small frequency offset from line centre. Calculations indicate a maximum contribution due to the resonance phenomena of about 300 KHz (for a 10 MHz offset) during the pulse risetime. Effects of this magnitude were not observable at a beat frequency of 10 MHz.

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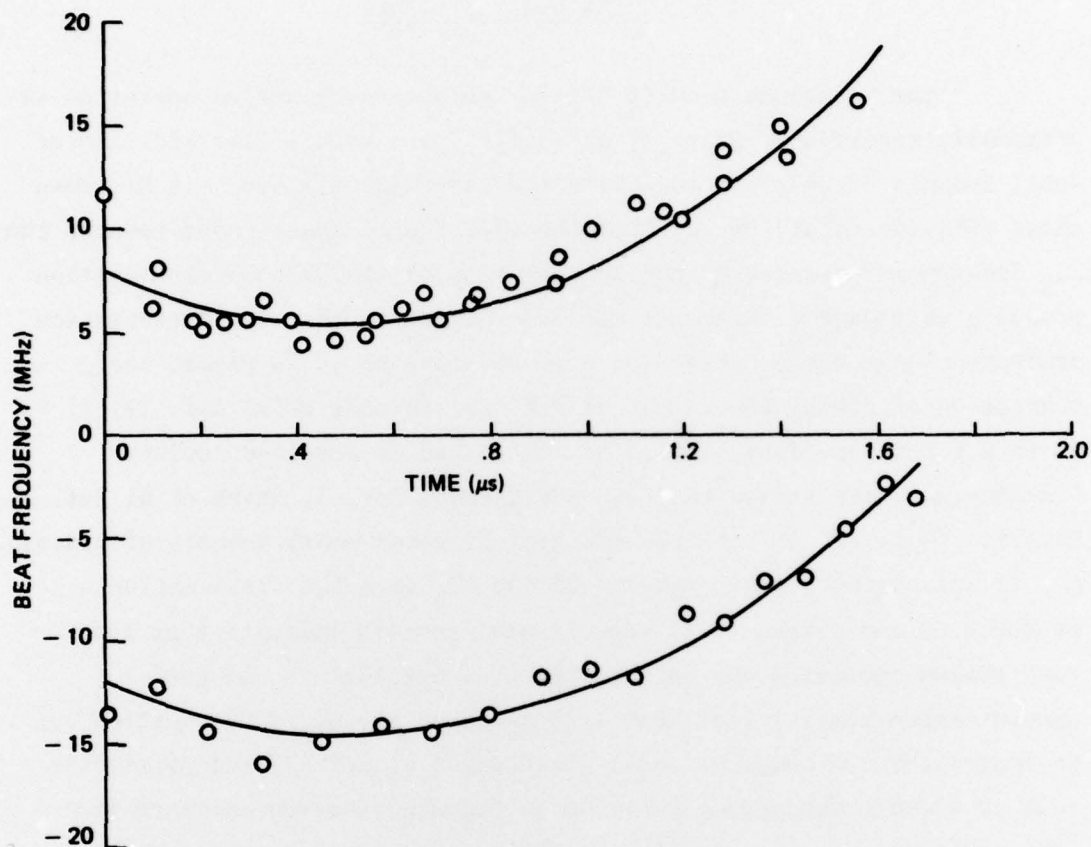


FIGURE 5 - Experimental instantaneous beating frequency for positive and negative initial cavity frequency offsets. The solid lines are used only as a guide.

4.0 OPERATIONAL LIFETIMES

The technique used to obtain the necessary sealed operation was originally reported by Stark et al (Ref. 1) and entails the addition of small amounts of hydrogen and CO to the laser gas mixture. It has been shown (Shields et al Ref. 2) that the addition of these gases reduces the CO_2 decomposition and thus the accumulation of the gaseous dissociation products is reduced. Since it has been suggested that the dissociation products change the negative-ion concentration so as to permit the transition of arcing (Davies et al Ref. 26, Shields et al Ref. 2), it is essential that the dissociation be controlled in a sealed device. Previous work has indicated (Pace and Lacombe Ref. 3, Stark et al Ref. 1, Shields et al Ref. 2) that the addition of these small amounts of hydrogen and CO stimulates the reformation of the CO_2 from the dissociation products CO and oxygen. The experimental results indicate that long-term sealed operation can be obtained provided that the oxygen concentration remains less than 1-2% and that the CO_2 decomposition can be controlled. A computer model (Shields et al Ref. 2) indicates that 1-2% of added oxygen greatly increases the negative-ion concentration (the dominant negative-ion CO_4^- for 2% added oxygen) and that the CO_2 decomposition (and thus the oxygen concentration) can be controlled by the addition of small amounts of H_2 and CO to the initial gas mixture.

To determine the effectiveness of these additives in the small laser under study, life tests were performed at a pulse repetition frequency of 0.5 Hz. As has been found previously (Pace and Lacombe Ref. 3) the addition of about 0.7% H_2 and 4% CO to obtain a mixture of $\text{He:N}_2:\text{CO}_2:\text{CO:H}_2 = 69.3:11:15:4:0.7$ gave a sealed lifetime of about 10^5 pulses at an output energy level of about 15-20 mJ/pulse and a peak power of about 100 kW in a single mode. The tests were terminated at about 10^5 pulses at which time the laser was still operating with an output of 15 mJ/pulse. Following the results obtained at a repetition rate of 30-40 pulses/s (Pace and Lacombe Ref. 3) it is expected that 10^6 pulses could be obtained using this gas mixture.

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To try and obtain a higher output energy, various tests were performed with different gas mixtures. It was found that stable operation could be obtained in helium-less mixtures over a pressure range of 40 to 100 kPa with various amounts of H_2 and CO and the ratio $N_2:CO_2$ in the range 0.3 to 0.6. A typical result is shown in Figure 6 for a mixture of $H_2:CO:N_2:CO_2 = 2:4:25:69$. It was found that stable sealed operation could be obtained at a charging voltage of 15 to 20 kV and a total pressure of about 54 kPa. The energy obtained using this gas mixture in sealed operation was 35 mJ/pulse with a peak power of about 150 kW (single-mode operation).

To date the laser has operated to 10^6 pulses using the helium-less mixture. The laser was still operating at this time, and a longer operational lifetime should be expected. It should also be noted that for all the lifetime tests the laser electrodes were mounted in a pyrex glass tube. The mirror supports were attached by means of clamps and O-rings, and mirror adjustment was provided by means of micrometer screws and a bellows arrangement.

As has been found previously (Stark et al Ref. 1) a grayish film develops upon the surface of the anode. This oxide layer suggests the presence of negative oxygen-bearing ions within the discharge, a fact predicted by the theory (Shields et al Ref. 2). This and other losses of oxygen to the surfaces of the laser seem to be responsible for a gradual decrease in CO_2 concentration. This leads to a gradual diminution of the laser power of about 5-10% over the 10^6 pulses and will probably cause the eventual termination of laser operation. Further tests will have to be performed to verify this assumption.

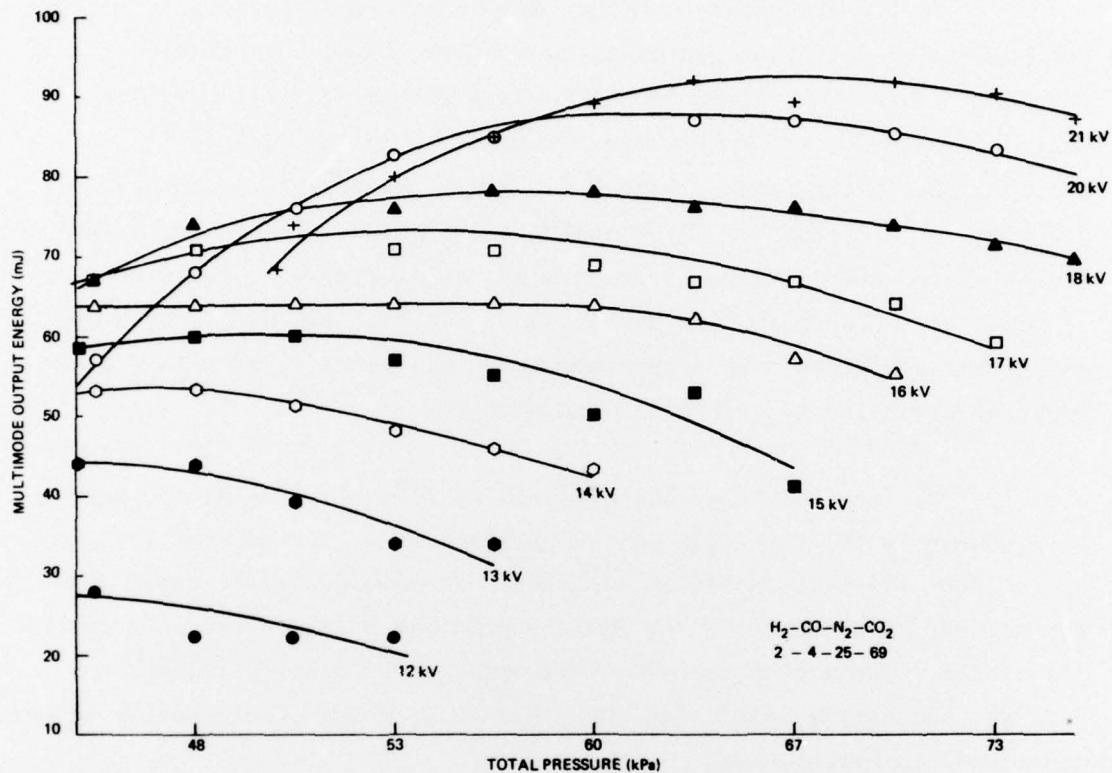


FIGURE 6 - Output energy against pressure and charging voltage for a mixture of $H_2:CO:N_2:CO_2 = 2:4:25:69$

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5.0 CONCLUSIONS

It has been demonstrated that single-longitudinal-mode operation can be obtained from a small TEA CO₂ laser without the necessity of using either a hybrid configuration or injection-locking techniques. It has also been shown that this type of laser can produce output pulse energies of 35 mJ at peak powers of 150 kW. Measurements of frequency sweeping during the tail of the pulse indicate that there is a 'chirp' of 5-6 MHz/μs.

During the experiments no attempts were made to stabilize the frequency of the TEA laser; however, for use as a heterodyne radar it may be possible to use a technique similar to that reported by Borzunov et al (Ref. 27). This entails placing the TEA laser and 'local oscillator' inside the same cavity and thus thermally induced changes in the cavity structure would cause identical frequency deviations in each laser and, hopefully, the effects on the beat frequency between the two lasers would be minimized.

It has also been demonstrated that it is possible to operate this type of laser in a sealed configuration to a least 10⁶ pulses without helium.

6.0 ACKNOWLEDGEMENTS

The authors would like to thank Dr. J.-L. Lachambre for calculations of the frequency sweeping due to the change in the resonant electric susceptibility. Discussions with M. Hale are also appreciated.

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CRDV, C.P. 880, Courcellette, Qué. G0A 1R0.

"A Compact, Sealed, Single Mode TEA-CO₂ Laser"
by P. Pace and M. Lacombe

Nous avons construit et scellé un laser CO₂ compact fonctionnant selon la technique de la double décharge et l'avons fait fonctionner en mode fondamental. Plus de 10⁶ impulsions ont été obtenues en régime scellé grâce à l'addition de petites quantités d'hydrogène et de CO au mélange gazeux initial. Nous avons également démontré qu'il était possible de faire fonctionner ce laser sans hélium avec une puissance de sortie, en mode fondamental, de l'ordre de 35 mJ/impulsion et une puissance crête de 150 kW. Le taux de répétition était de 0.5 s⁻¹.

Dans le but d'obtenir l'oscillation dans le mode fondamental, nous avons gardé la longueur totale de la cavité du laser à 18 cm. Cette courte cavité permet l'oscillation d'un seul mode longitudinal quand la fréquence de la cavité est entretenue près de la fréquence centrale de CO₂. Des mesures de batttement de fréquence, effectuées à l'aide d'un laser stabilisé CO₂ à onde entretenue, indiquent une déviation de fréquence d'environ 5-6 MHz/us dans la queue de l'impulsion. (NC)

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"A Compact, Sealed, Single Mode TEA-CO₂ Laser"
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A compact, sealed, TEA-CO₂ laser utilizing a double-discharge technique has been constructed and operated under single-mode conditions. Sealed operational lifetimes exceeding 10⁶ pulses have been obtained by the addition of small quantities of hydrogen and CO to the initial gas mixtures. It has also been found that operation without helium is possible giving single-mode output energies of about 35 mJ/pulse at peak powers of about 150 kW. The pulse repetition frequency was 0.5 s⁻¹.

To obtain single-longitudinal-mode operation, the laser cavity was kept at an overall length of 18 cm. This short laser cavity allowed the oscillation of only one longitudinal mode when the frequency of the cavity was tuned closely to the CO₂ line centre frequency. An iris was used to restrict transverse modes to the TEM₀₀ mode. Beat frequency measurements using a stable, CW CO₂ laser indicate a 'chirp' of about 5-6 MHz/μs in the tail of the pulse. (U)

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